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Dispersion Analysis of the XM881 Armor-Piercing, Fin-Stabilized, Discarding Sabot (APFSDS) Projectile

by Thomas F. Erline
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Abstract

This study compares the results of a dispersion test with mathematical modeling. A 10-round group of modified 25-mm XM881 armor-piercing, fin-stabilized, discarding sabot (APFSDS) projectiles was fired from the M242 chain gun into a designated target. The mathematical modeling results come from BALANS, a product of Arrow Tech Associates. BALANS is a finite-element lumped parameter code that has the capability to model a flexible projectile being fired from a flexible gun. It also has the unique feature of an automated statistical evaluation of dispersion. This study represents an effort to establish a combined experiment and simulation approach to reduce system error.

Acknowledgments

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1. Introduction

The U.S. Army has a need to improve its understanding of the effectiveness of medium-caliber cannon systems. One of the methods for advancement toward this understanding is to perform experimental aerodynamic jump tests and mathematical modeling that simulates the jump tests. One fielded system of major interest is the 25-mm M242 Autocannon, which is found on the Bradley Fighting Vehicle. This gun system was selected for study by the U.S. and German Defense Exchange Agreement No. 1132. This system is ideal for setup in a small-caliber range, such as the Aerodynamics Range Facility at the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground (APG), MD.

The current service round, used with the 25-mm M242 Autocannon, is the M919 armor-piercing, fin-stabilized, discarding sabot (APFSDS) projectile used for armor penetration. This round has a depleted uranium penetrator that would contaminate the experimental facility. Therefore, the XM881, which has a tungsten penetrator and was a precursor of the M919, presents itself as a suitable substitute. The XM881 has a flight vehicle that is geometrically similar to the M919, including matching threads for fitting the sabot; however, the discarding sabot of the XM881 was totally different from the M919. To better emulate the M919, it was decided to replace XM881 sabots with the sabots used on the M919.

The dynamic state of a projectile at shot exit is determined in part by the in-bore launch disturbances experienced by the projectile as it traverses the length of the barrel. A contributing factor is the initial misalignment of the projectile's principal axis and center-of-gravity (CG) offset with respect to the bore centerline. As the projectile is driven axially downbore by the propellant gas pressure, it is also forced to travel a lateral path that is determined by static and dynamic curvatures. Tube droop in the vertical plane is a gravity-induced static curve, and the bore straightness profile is a static curve due to the manufacturing processes' inability to produce a perfectly straight bore. The firing of the gun produces an array of complex interdependent events. Axial travel of the projectile and propellant gas pressure will impart forces on the gun for recoil and slight bending in the barrel. The projectile reacts in flexure to the massive barrel,

and the barrel responds to the projectile loads. The dynamic lateral path then becomes a boundary condition of projectile balloting.

The balloting analysis program, BALANS, from Arrow Tech Associates, Inc., was chosen for this study because of its multifunctional abilities. It has the capability to perform a single shot deterministic case in either two or three dimensions and target impact dispersion analysis using a stochastic approach.

Under this mission for investigating the experimental performance of the XM881, it is believed that good agreement between the experimental results and modeling results with the BALANS program will allow modeling to point to areas that need improvement. This is especially true in the area of gun tube straightness and interactions between the projectile and the gun tube. In this study, for example, both experiment and modeling show the in-bore balloting reactions to be a significant contribution to dispersion.

2. Experimental Approach

2.1 Overview of the Experiment. The M242 chain gun was setup at the Aerodynamics Range of ARL, APG. A schematic of the test setup is shown in Figure 1. Two eddy probe stations that measure lateral displacements were positioned about the muzzle brake of the gun to capture the muzzle motion. A pressure probe trigger was located just outside of the muzzle to start the experimental equipment. A sabot catcher plate was positioned several meters from the muzzle. Six orthogonal x-ray stations were positioned within 2 ms of the muzzle to capture velocity, yaw, and yaw rates. There were 25 orthogonal shadowgraph stations to measure the flight vehicle motion (see Figure 2). At 100 m from the muzzle, a target setup recorded shot fall. The muzzle displacements, pointing angles, transverse velocity, and angular velocity were determined using data reduction analysis techniques found in Haug and Bornstein [1].

2.2 Description of the XM881. The XM881 is a 25-mm APFSDS experimental round that has gone through a number of design iterations. The XM881 specimens available did not match

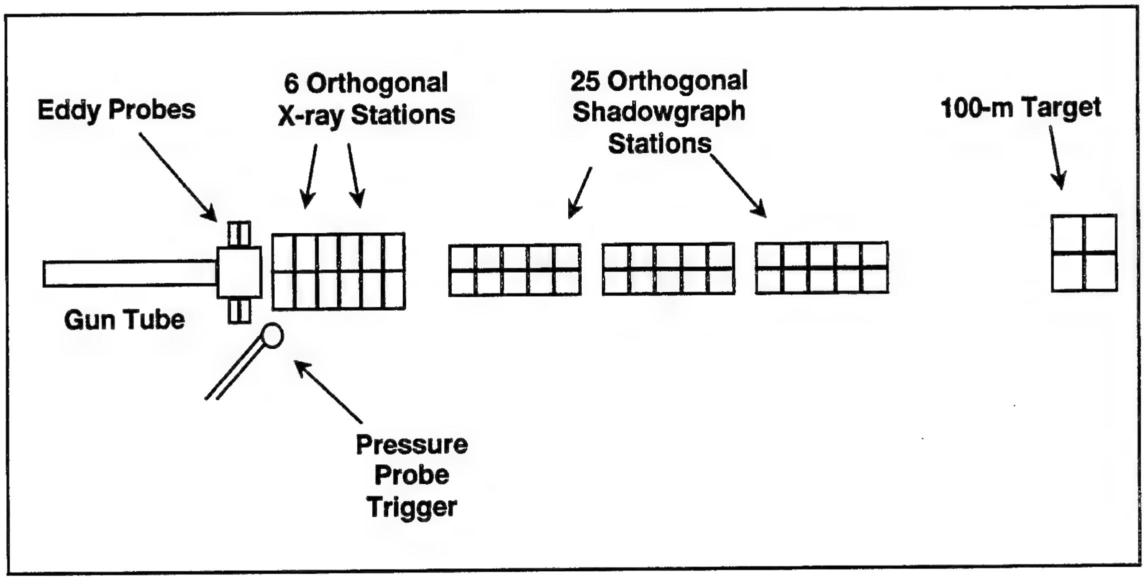

Figure 1. Jump Test Instrumentation.

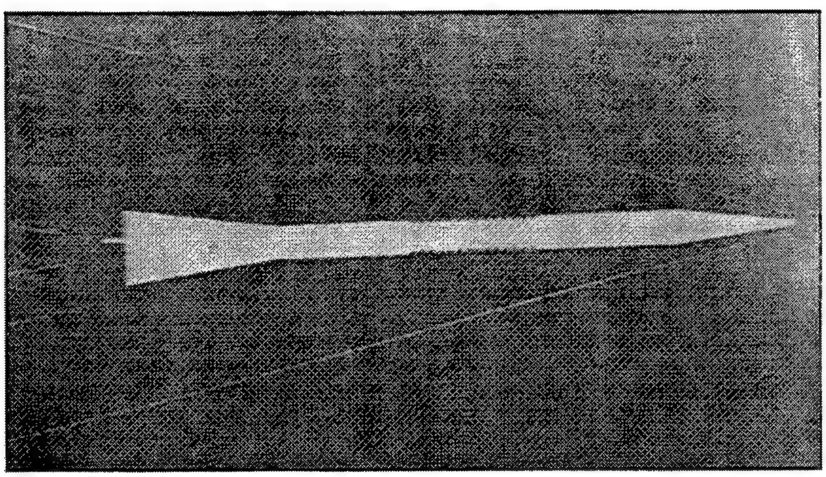

Figure 2. XM881 Flight Vehicle at Mach 4.0.

the particular version of the penetrator drawings found. Therefore, detailed measurements were performed. The total length of the flight vehicle is 153.0 mm with the penetrator length of 82.8 mm and threaded length of 29.4 mm starting at 64.4 mm from the base of the flight vehicle. (Refer to Figure 2 showing a print of a shadowgraph of the flight vehicle from the test.) The original sabots were removed from the flight vehicle and replaced with those found on the M919.

2.3 Bore Straightness. The M242 chain gun was set up with barrel serial number (SN) 273, which was measured for centerline straightness and bore gauged for service condition. The vertical (without gravity droop) and horizontal centerline referencing the rear face of the tube (RFT) of SN 273 is shown in Figure 3. The manufacturing irregularities noted in the centerline are typical with positive up and to the gunner's right.

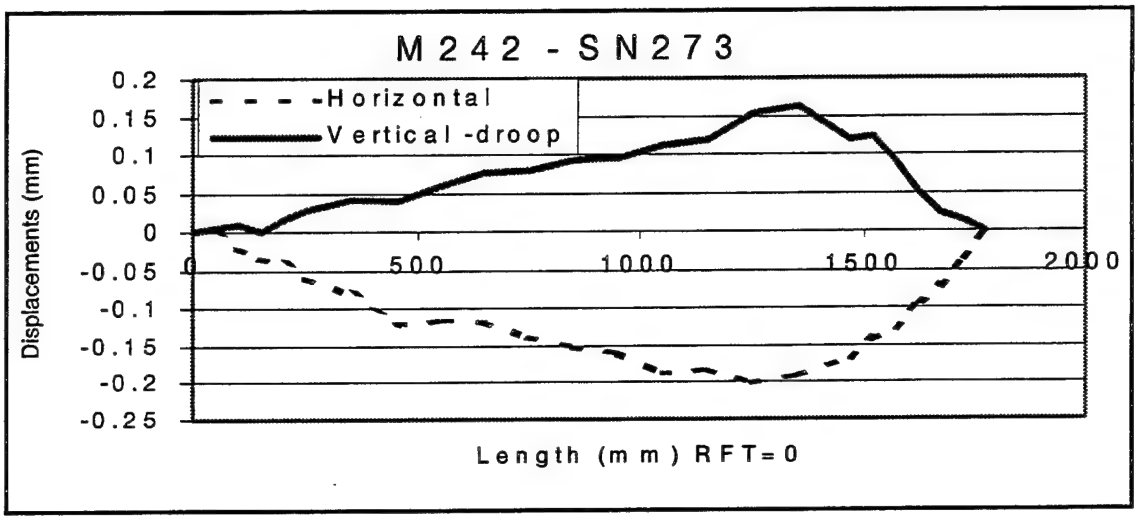

Figure 3. M242 Barrel SN 273 for the 25-mm Chain Gun.

2.4 Experimental Results. The experimental results are utilized in jump and dispersion models that are defined in Plostins et al. [2]. The means of major angular components of jump and dispersion are displayed in Figure 4 in milliradians. The muzzle pointing angle component is noted as "PA." The muzzle of the gun has transverse velocity noted as "CV," which imposes on the projectile at shot exit. The angular deviation of the projectile center of gravity relative to a coordinate system attached to the muzzle at shot exit is known as projectile "CG" jump. The "CG" jump is caused by in-bore balloting, muzzle blast, projectile mechanical disengagement, and sabot discard. The component noted as "AJ" is aerodynamic jump, which is the mean angular deviation of the projectile swerve trajectory. There was no measurable evidence of disturbance from sabot discard on the projectile "CG" jump. The sabot discard was completed within 0.15 m from muzzle, which is too close to the muzzle to capture in the x-ray stations. In Figure 4, positive is up and to the right.

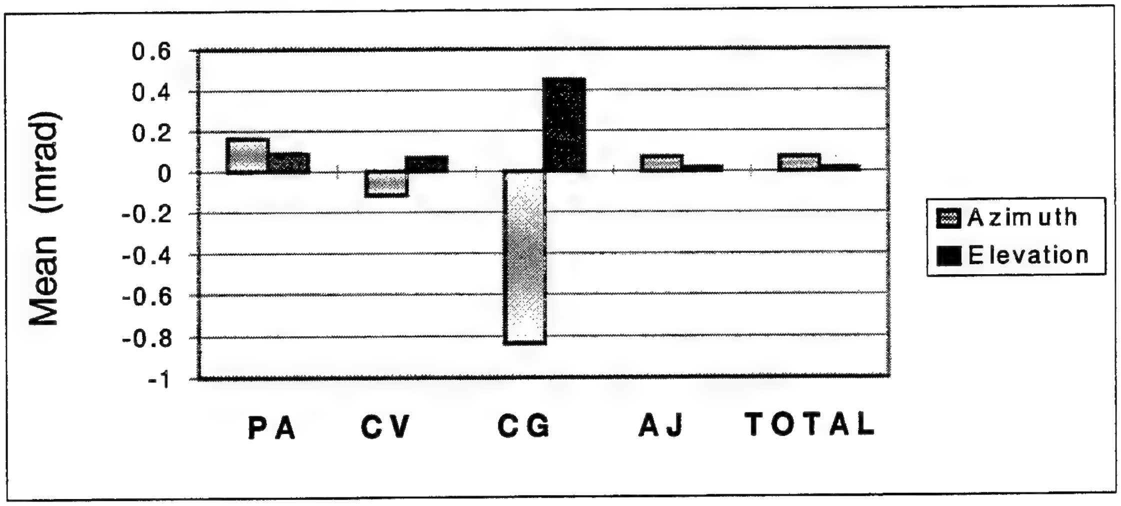

Figure 4. The 25-mm XM881 Means of Jump Components.

The standard deviations of the components of jump are displayed in Figure 5. The dispersion model may be simple if the total dispersion is the result of the sum of the independent individual jumps. The square of the standard deviations of the individual jump components will sum to the square of the impact dispersion. This empirical model appears to be best suited for this type of experiment.

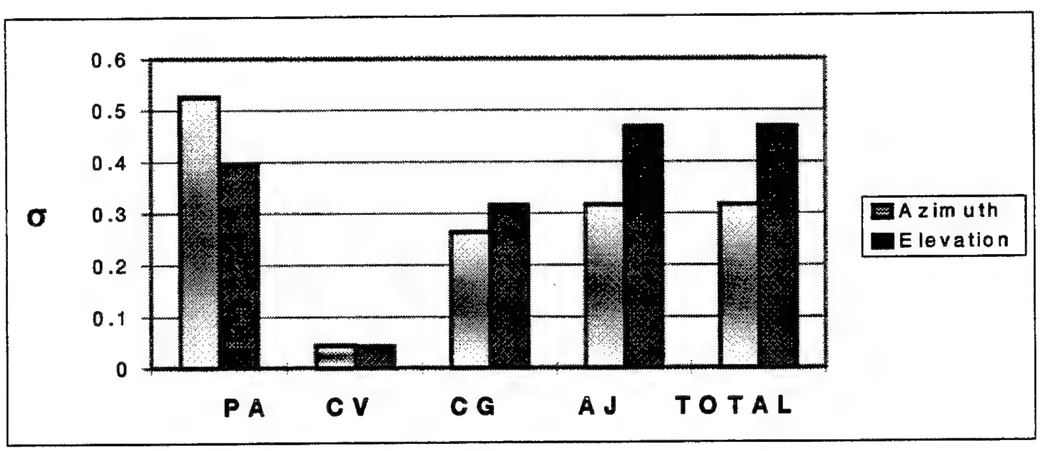

Figure 5. The 25-mm XM881 Dispersion of Jump Components.

3. Analytical Approach

3.1 Overview of BALANS. BALANS [3] simulates the dynamic response and interaction of a flexible projectile and a flexible gun tube during in-bore travel. It also includes the effects of a curved bore profile. The simulation utilizes individual models of the projectile and gun tube, in a time step iterative solution. Pertinent motion and load data are periodically saved during the analysis to produce selective summary graphical displays. BALANS takes advantage of the interior ballistics simulation and CG offset calculations of PRODAS [4] and an automatic lumped parameter modeling capability to assist in building a BALANS model.

The analytical procedure utilized in BALANS presupposes that the projectile is initially misaligned within the gun tube due to manufacturing tolerances. During firing, this misalignment produces secondary forces, causing transverse displacement and yawing motion of the projectile as it travels from breech to muzzle. The resulting yaw angle, angular rate, and transverse velocity at muzzle exit are then analyzed for their effects on dispersion. It should be noted that BALANS calculates the projectile state (yaw, yaw rate, and transverse velocity) at muzzle exit while the experimental setup determines the state of the tube and bore at the projectile exit.

Figure 6 contains a flow diagram of this stochastic method for predicting dispersion. Whether trying to predict dispersion on a new design or solve a dispersion-related problem on a current design, the approach is very similar. It begins with gathering basic technical information such as manufacturing dimensional data, assembly drawings and/or specifications, and analytical results from other analyses or tests such as finite element analyses or experimental results of the sabot front borerider. This information is critical to building the accurate analytical model of the projectile to be used during all analyses within this approach. From this information, a tolerance study can also be performed for input into the in-bore balloting analysis.

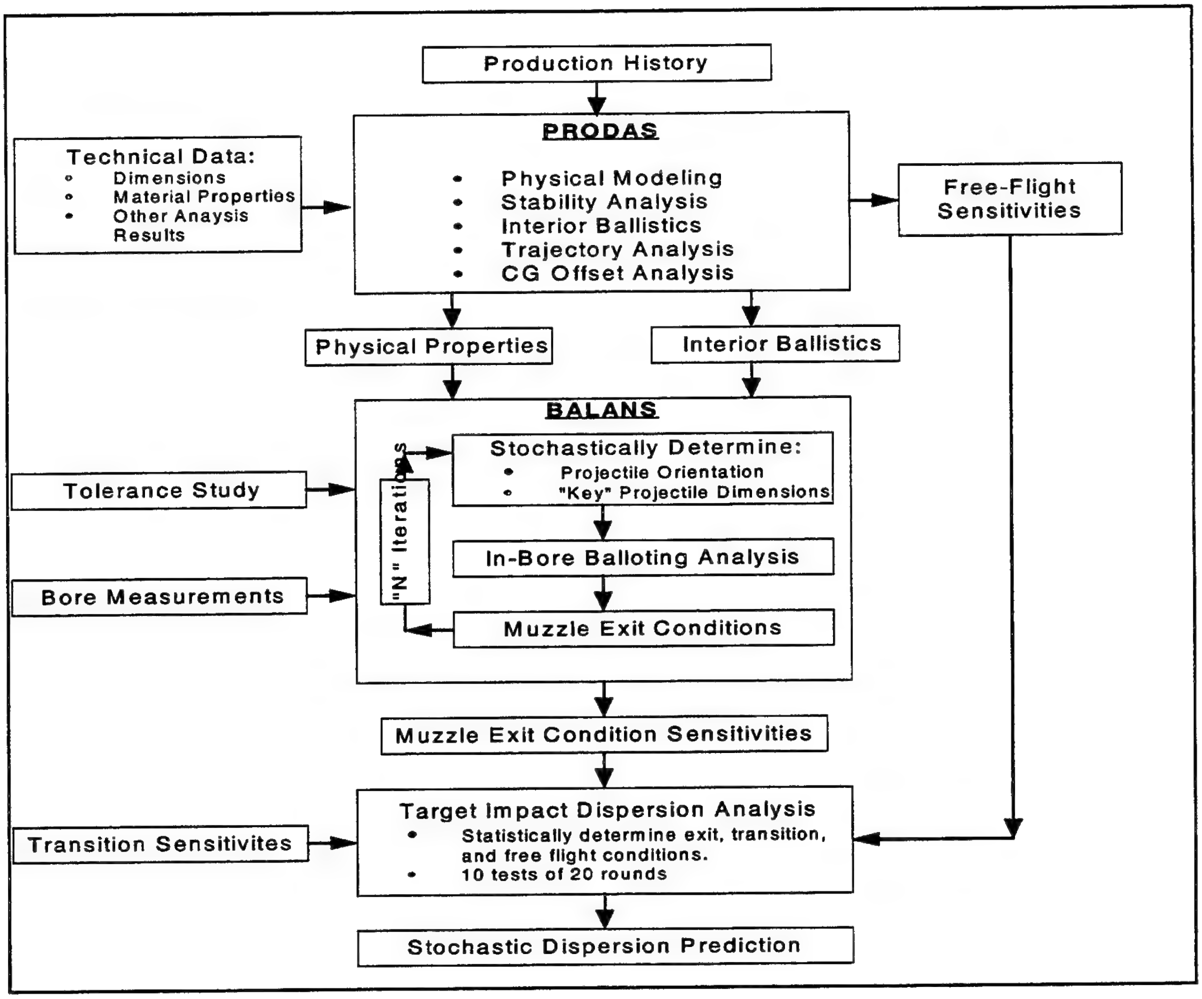

Figure 6. Analytical Approach to Predicting Dispersion.

The second piece of information required is production history information such as Statistical Process Control (SPC) information. Even if working with a new projectile design for which there is no production history, it is valuable to obtain this information for a similar design or a projectile with similar characteristics.

Because some of the inputs to this approach are statistical in nature, the historical data provide a foundation from which to derive the statistical information.

The last type of information required is test and/or measurement that is important to predicting dispersion but is not derived from analysis. This includes bore centerline

measurements, boresight errors inherent within a test fixture or boresight tool, known sabot discard issues from tests of similar sabots, etc.

As can be seen in Figure 6, the drawings, production history, and results from previous analyses are used for physical modeling of the projectile, which in turn is the basis for several analyses to be described in the following sections. Each of the analyses results in dispersion component sensitivities that are then used in predicting dispersion.

3.2 BALANS Model of the XM881. The basic inputs for the BALANS in-bore balloting analysis are a lumped parameter model of the projectile that properly characterizes its mass properties and flexibility, a forcing function, and several distances and runouts that are used to orient the projectile within the gun tube. The lumped parameter model is generated automatically from the PRODAS geometric model.

Figure 7 is an example of the XM881 as a lumped parameter model automatically generated from PRODAS. As shown, the upper half of the model is the actual projectile as generated from PRODAS. The lower half attempts to mirror the upper half by reflecting the lumped parameter node/element model.

The forcing function required for the balloting analysis is provided directly from the PRODAS interior ballistics analysis module. PRODAS uses the Baer-Frankl methodology to simulate combustion of propellant grains and calculate the time-dependent parameters of base pressure (which is applied to the projectile aft of the obturator during the balloting analysis), spin velocity and acceleration (which is used to calculate centrifugal forces during in-bore travel), and axial acceleration (which is used to calculate axial forces during in-bore travel). Transverse forces are calculated from the induced balloting motion.

In addition to the lumped parameter model, the dispersion analysis requires manufacturing dimensional and tolerance information and transition and free-flight sensitivity information. The

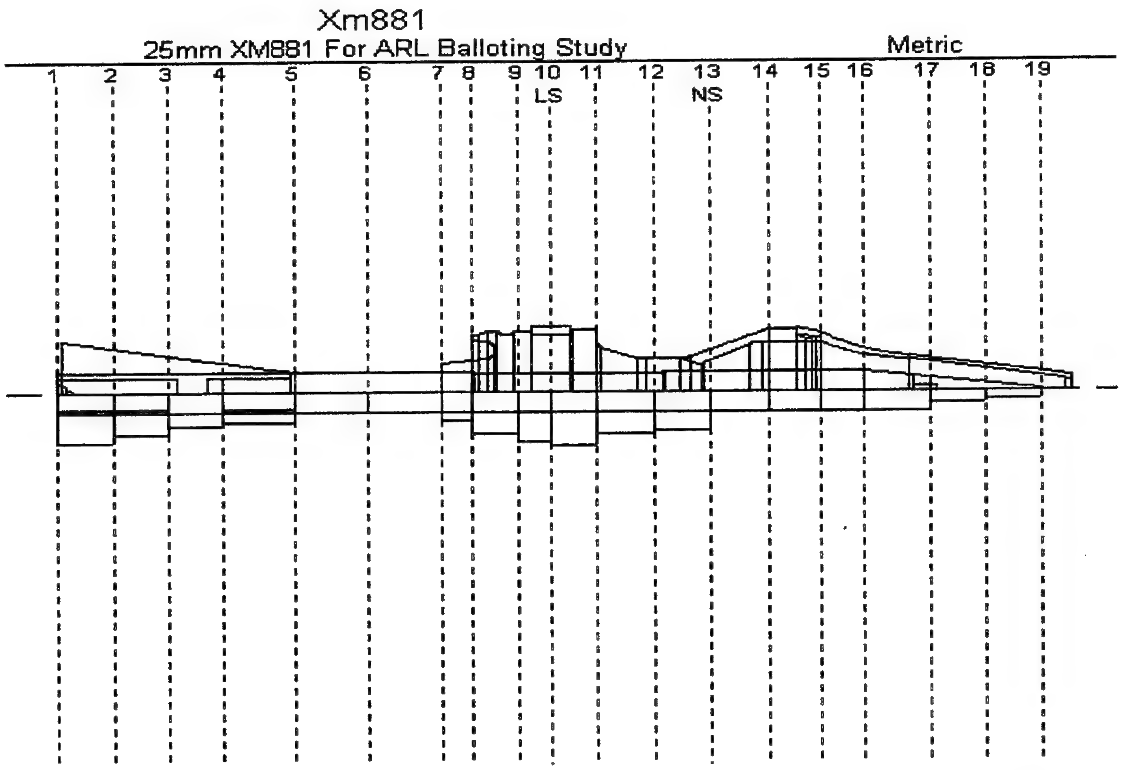

Figure 7. Graphical Representation of the XM881 Lumped Parameter Model.

manufacturing information consists of several critical dimensions and tolerances necessary for in-bore balloting. These define the locations of the projectile/gun tube interfaces and some of the critical projectile dimensions which affect dispersion. The statistical in-bore balloting analysis uses these dimensions and their tolerances to randomly orient the projectile in the gun tube. Several hundred in-bore balloting analyses are generally required to obtain statistically valid muzzle exit yaw, yaw rate, and transverse velocity predictions [5].

The transition and free-flight sensitivity information is used to determine those components of dispersion after the projectile has left the gun tube. Transition sensitivities are separated into sabot discard and boresight sensitivities. Errors induced by sabot discard may have significant variation from one projectile configuration to another. They have both a physical component that can occur due to asymmetric loads applied to the core during discard and an aerodynamic interference component. Sabot discard is the least well understood of the major contributors to dispersion and therefore is generally determined from test, observation, and/or experience.

Boresight errors are the errors associated with pointing the gun at the target. Boresight errors vary between calibers, gun crews, and instrumentation.

The free-flight dispersion component sensitivities include muzzle velocity, aerodynamic jump, aerodynamic trim angle, crosswinds, and aerodynamic/mass asymmetries. All of these parameters are determined via trajectory analysis within PRODAS as follows:

- The muzzle velocity sensitivity factor is the drop variation due to muzzle velocity variation and can be calculated by comparing the drop of trajectory simulations made by perturbating muzzle velocities.

- The aerodynamic jump sensitivity relates dispersion to the muzzle exit yaw rate of the projectile. This factor is dependent upon the physical and aerodynamic characteristics of the projectile as well as the projectile spin and velocity.

- The crosswind sensitivity of the projectile is determined by trajectory simulations of the projectile flight to the range of interest both with and without a nominal crosswind applied.

- The aerodynamic trim angle of a projectile configuration (due to manufacturing tolerances) may be calculated from PRODAS predictions of the body (alone) and fin (alone) center of pressure and normal force coefficients, and from the expected one-sigma value of the angular misalignments of the nose and tail sections.

- The aerodynamic/mass asymmetries factor is determined by simulating trajectories with a trim angle assumed to be oriented at orthogonal and diametrically opposed orientations.

3.3 Deterministic Analysis. Once the lumped parameter model of the projectile and gun system is finished, one needs to run test cases, starting with the most basic analysis before proceeding to more complex simulations. First, run the simplest case—for example, a two-dimensional single-shot simulation using a straight centerline including gravity droop.

When the results appear reasonable, then move on to a simulation that includes the measured centerline from SN 273. Now, one simple way of obtaining insight from the modeling results is to compare the results from the straight centerline to the measured centerline of SN 273. In Figure 8(a), the projectile lateral forces resulting from interaction with a smooth, straight centerline are shown. Though the loads are low, it is immediately apparent that balloting causes high-frequency disturbance. In Figure 8(b), the projectile lateral forces resulting from interaction with a centerline that includes manufacturing irregularities are shown. The loads are only slightly higher except for some higher forces noted near shot exit delivered to the rear contact of the projectile.

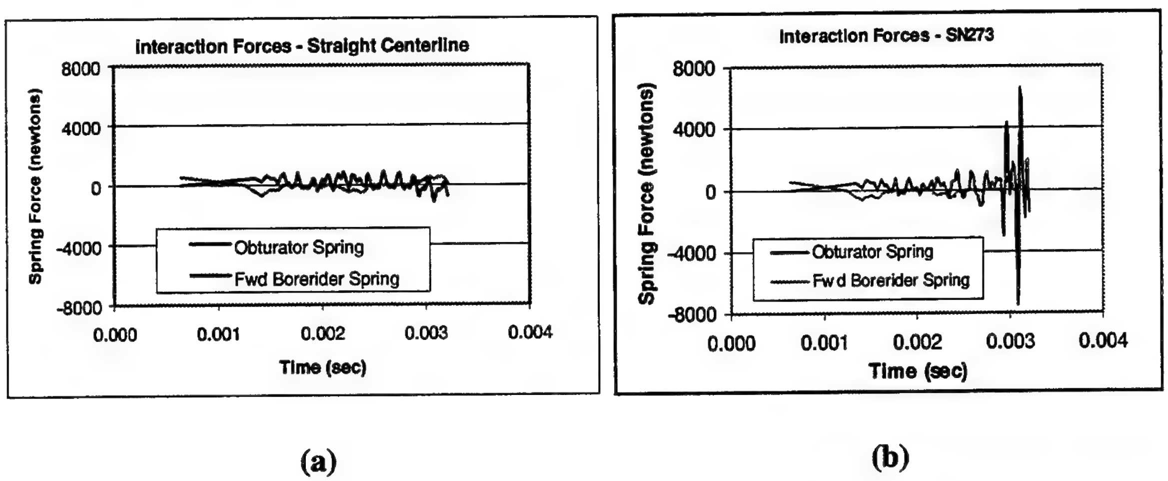

Figure 8. Interaction Forces: (a) Straight Centerline, (b) SN 273.

The deterministic analysis provides a detailed analysis at each node in the lumped parameter model in terms of bending moments, shear forces, nodal displacements, projectile shape at each time step, and exit conditions. It is equivalent to performing a single-shot experiment to investigate issues other than dispersion. Since the analysis presupposes an initial projectile orientation in the gun tube, which is difficult to determine experimentally, the deterministic analysis has limited usefulness when trying to evaluate overall projectile performance parameters such as dispersion.

3.4 Stochastic Analysis. Since production history information such as SPC information does not exist for the XM881 specimens in our inventory, the parameters required for input had to come from either measurements or estimates based on M919 data. For the sensitivity values found in Table 2, the muzzle velocity data come from the experiment. Aerodynamic jump, yaw factor, and spin rate come from the PRODAS segment. Boresight, sabot discard, and miscellaneous error numbers are engineering best guess values based on experience with similar projectiles. For simplicity, values that were assumed to be zero, such as wind factors, aerodynamic, and mass asymmetries, are not shown in the table.

Tables 1 and 2 contain sensitivity data and manufacturing information required for the simulation. Generally, these data are obtained from previous simulations, testing, drawings, and/or SPC data collected by the manufacturer. For this simulation, the source of the data was either through measurements (meas.) or from engineering estimates (est.) that are based on previous experience in simulating and testing of similar rounds.

Table 1. XM881 Sensitivity Data

Characteristic	Value	Data Source
Aerodynamic Jump Factor (dimensionless)	0.030	est.
Muzzle Velocity Standard Deviation (m/s)	8.419	est.
Muzzle Velocity Factor (dimensionless)	0.005	est.
Boresight Error (dimensionless)	0.050	est.
Sabot Discard Error (dimensionless)	0.050	est.
Miscellaneous Errors (dimensionless)	0.100	est.
Muzzle Velocity (m/s)	1398.4	meas.
Initial Yaw Factor (mils)	0.010	est.
Muzzle Spin Rate (rad/s)	2900.0	est.

The BALANS dispersion results presented here in Table 3 are the result of 10 different simulations of 10 rounds each stochastically determining projectile orientations and other key

Table 2. Manufacturing Tolerance Information

Characteristic	Value (mm)	Data Source
Distance to Obturator	63.0941	meas.
Distance to Forward Spring	101.143	meas.
Distance to Bore Rider	110.236	meas.
Bore Diameter	25.100	meas.
Forward Bourrelet Mean Diameter	24.970	est.
Forward Bourrelet Standard Deviation	0.015	est.
Forward Bourrelet Runout (Mean to Penetrator)	0.025	est.
Forward Bourrelet Runout Standard Deviation	0.010	est.
Rear Bourrelet Runout (Mean to Penetrator)	0.025	est.
Rear Bourrelet Runout Standard Deviation	0.010	est.
Sabot Inside Diameter at Forward Bourrelet	8.273	meas.
Sabot Inside Diameter at Forward Bourrelet Standard Deviation	0.000	est.
Core Outside Diameter at Forward Bourrelet	8.273	meas.
Core Outside Diameter at Forward Bourrelet Standard Deviation	0.000	est.

Table 3. Simulated TID Results of 10 Simulations of 10-Round Tests

Simulation No.	Horizontal (mrad)	Vertical (mrad)
1	0.320	0.418
2	0.384	0.469
3	0.377	0.463
4	0.350	0.441
5	0.402	0.484
6	0.321	0.419
7	0.460	0.533
8	0.292	0.397
9	0.381	0.467
10	0.408	0.489
Average	***0.369***	***0.458***
Standard Deviation	***0.050***	***0.040***

dimensions as described earlier to develop the muzzle exit conditions of yaw, yaw rate, and center of gravity velocities. To perform the target impact dispersion analysis, the muzzle exit sensitivities are combined with the transition sensitivities and free-flight sensitivities. Table 4 shows the components of dispersion for one of the simulations.

Table 4. Components of Dispersion (From Simulation No. 3)

Dispersion Component	Horizontal (mrad)	Vertical (mrad)
Yaw Rate	0.304	0.304
Muzzle Velocity	0.000	0.269
Windage	0.000	0.000
Boresight	0.050	0.050
Sabot Discard	0.050	0.050
Aero/Mass Asymmetries	0.000	0.000
Yaw Angle	0.001	0.001
Transverse Velocity	0.058	0.058
Muzzle Spin	0.204	0.204
In-Bore Total (Yaw Rate + Yaw Angle + Transverse Velocity + Muzzle Spin) = 0.371		

4. Comparison Between Experimental and Analytical Results

This project is still a work in progress. The Aerodynamics Branch of ARL and Arrow Tech Associates are continuing the dialog necessary to resolve all the parameters definitions and understand all the translations that may be required to make BALANS output results correlate to the similar quantities that are used in the experimental arena. At the present time, the two parties believe the bottom line quantities of horizontal and vertical standard deviations (sigmas) for total dispersion can be compared directly (see Table 5).

Table 5. Total Dispersion Comparison

Test	Sigma - Horizontal (mrad)	Sigma - Vertical (mrad)
Experiment (10 rounds)	0.470	0.570
Simulation (10 simulations each with 10 rounds)	0.292	0.397
Minimum	0.460	0.533
Maximum	0.369	0.458
Mean (of 10 simulations) Standard Deviation (of 10 simulations)	0.050	0.040

From a strict comparison point of view, the differences between the experimental values and the mean of the simulation values appear to be quite large. However, the difference between the minimum and maximum values of the ten simulations is also significant. This implies that there is some variability in a 10-round sample size. Another source for the differences is in the number of simulation parameters that had to be estimated.

5. Summary and Conclusions

The full scope of correlating the experimental work with the modeling efforts is incomplete at this time. However, despite the lack of closure on this project, this work has brought the following insights:

- Use of this combined experimental and analytical approach can lead to more effective test plans by providing engineers with the relative magnitude of dispersion improvement to be expected by changes in a configuration.

- The experimental approach complements the analytical approach by providing accurate aerodynamic coefficients, a necessary ingredient to determining the free-flight sensitivities for the analytical approach.

- The BALANS analytical approach is useful in the investigation of piece-part dimensional tolerances and their effect on dispersion.

- Since dispersion is a combination of random independent and interdependent events, statistics becomes an important issue. The most important issue is whether one can experimentally predict an overall projectile performance parameter such as dispersion from a 10-round group.

- When combining the experimental approach with the mathematical simulation approach, the modeler should be involved in the experimental methodologies to allow for more understanding of detailed comparisons.

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This study compares the results of a dispersion test with mathematical modeling. A 10-round group of modified 25-mm XM881 armor-piercing, fin-stabilized, discarding sabot (APFSDS) projectiles was fired from the M242 chain gun into a designated target. The mathematical modeling results come from BALANS, a product of Arrow Tech Associates. BALANS is a finite-element lumped parameter code that has the capability to model a flexible projectile being fired from a flexible gun. It also has the unique feature of an automated statistical evaluation of dispersion. This study represents an effort to establish a combined experiment and simulation approach to reduce system error.

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